
A comparison between two electronic apex locators: an *in vivo* investigation

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Abstract

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Aim To compare *in vivo* the Apex Finder and Root ZX electronic apex locators (EALs) at five different stages during root canal instrumentation.

Methodology The Apex Finder and Root ZX were used in 64 teeth with either vital or necrotic pulps. Informed consent was obtained by each patient under a study protocol approved by an ethical committee from the University of Trieste. Measurements were made: (stage 1) before instrumentation and irrigation; (stage 2) after brief filing, irrigation with 70% isopropyl alcohol and partial drying; (stage 3) after canal lubrication with EDTA gel (RC-Prep); (stage 4) after complete instrumentation and irrigation with NaOCl 5%; (stage 5) after drying of the final instrumented canal. Stages 2, 3 and 5 were considered low canal conductivity conditions and stage 4 as high. Teeth were then extracted and a size 15 K-file was inserted until its tip was observed under stereomicroscope to reach the foramen and the corresponding length was recorded to an accuracy of

0.25 mm and compared with values derived from the EALs.

Results The data revealed 133 unstable measurements (out of 640); some (68) related to low canal conductivity conditions (more frequently for Root ZX, 67; $P < 0.05$), and others (63) related to NaOCl presence in the canal (more frequently for Apex Finder, 58; $P < 0.05$). Accuracy was calculated only on stable measurements. The Root ZX showed significantly ($P < 0.05$) more precise measurements overall (-0.03 ± 0.39 mm) compared with the Apex Finder (-0.31 ± 0.46 mm). Under dry canal conditions the Apex Finder provided the greatest accuracy (-0.0 ± 0.21) compared with the Root ZX (-0.05 ± 0.32) (significance $P < 0.05$).

Conclusions Under the five different clinical situations both EALs revealed accurate measurements. Apex Finder was negatively influenced by NaOCl in the root canal. The Root ZX was more frequently unable to reveal stable measurements in low conductivity canals.

Keywords: electronic apex locators, impedance, root canal length.

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Introduction

The apical constriction is the landmark at which endodontic instrumentation should preferably end (Pratten & McDonald 1996, Dunlap *et al.* 1998). Radiographic determination of working length has

been considered the most appropriate method, however, it is impossible on the radiographic film to consistently detect the major and minor foramina, or cemento-dentinal junction (CDJ) (Stein *et al.* 1990). Kuttler (1955) showed that the apical constriction (minor foramen) was 0.524–0.659 mm coronal to the anatomic apex of the tooth (apical foramen, major foramen), and Lee *et al.* (2002) revealed that CDJs were not always detectable even under microscopic examination. Furthermore, Lee *et al.* (2002) reported that more than 50% of samples had only a vague CDJ

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configuration, whilst no definitive determination of a CDJ was possible on the other specimens. It has been declared that the CDJ, the end-point of the root canal system, is an histological and not a morphological landmark (Kuttler 1955).

Previous studies demonstrated that electronic apex locators (EALs) can determine canal length within 0.5 mm from the apical constriction in 75% (Fouad *et al.* 1990, Hembrough *et al.* 1993) to 88% of canals (Hembrough *et al.* 1993). Recently, Lee *et al.* (2002) reported in their study that most of the file tips ended at the major foramen regardless of the existence of a detectable CDJ suggesting that the major foramen was more reproducible, compared with the CDJ, for accuracy studies.

The development of EALs began in 1942, when it was reported that the electrical resistance between the periodontal ligament and the oral mucosa *in vivo* was a constant value of ~ 6.5 k Ω (Suzuki 1942). Later Sunada (1962) introduced the principle of the 'biological characteristics theory' into clinical practice, stating that the EALs could read the apex by measuring the differences of electrical resistance values between the periodontal ligament and the oral mucosa.

The EAL of Sunada (1962) used continuous wave current that gives a polarization effect on the electrodes, thus negatively affecting their performance. This led to the development of EALs supplied by alternating current (Inoue 1973). These second generation EALs are characterized by a single frequency of alternating current to detect changes in the canal impedance.

Despite considerable developments over the years, the major disadvantage with these EALs is related to the fact that the canal needs to be reasonably free of electrically conductive material in order to achieve an accurate reading (Ushijama 1983, Ushijama *et al.* 1988, Fouad & Krell 1989).

The third generation of dual frequency EALs has attempted to overcome or minimize this problem; in fact these devices are also based on alternating current, but they operate on the principle that the impedance difference between electrodes depends on the signal frequencies used. In particular, the Endex (Osada Electric Co., Tokyo, Japan) calculates the difference between two potentials of the root canal with composite sine wave current sources of two frequencies (Yamashita 1990), whilst the Root ZX (J. Morita Corp., Kyoto, Japan) applies a 'ratio method' for measuring the root canal length (Kobayashi *et al.* 1991b, Kobayashi & Suda 1994, Kobayashi 1995). The Root

ZX simultaneously measures the impedance of two different frequencies, calculates the quotient of the impedances, and expresses this quotient as a position of the electrode (file) inside the root canal. Nguyen *et al.* (1996) declared the Root ZX was able to identify the apical constriction location even when this anatomic landmark had been eliminated.

Nevertheless, the third generation apex locators should function more accurately than second generation ones, especially with conductive solutions inside the canals. However, their accuracy within 0.5 mm of the apical constriction has been reported to be from 82% (Pagavino *et al.* 1998) to 100% of the measurements (Czerw *et al.* 1995) with Root ZX, and 90% (Frank & Torabinejad 1993) for the Endex. Thus, the accuracy of the third generation EALs appears to be the same as the accuracy of the second generation EALs with one frequency.

Studies have confirmed the accuracy of the Root ZX in the presence of sodium hypochlorite (NaOCl) inside the canal system (Pratten & McDonald 1996, Dunlap *et al.* 1998), revealing that the Root ZX is not adversely affected by the presence of a conductive agent inside the canal (Meares & Steiman 2002).

The rationale of the present study arises from the consideration that the impedance measurements performed by second generation EALs are basically resistance measurements, aimed to reveal the electrical circuit resistance variation that occurs as the file approaches the apical constriction. On the contrary, the impedance measurements performed through the third generation EALs are mainly aimed to detect capacitance variations (Kobayashi & Suda 1994). Impedance has been investigated in many biological fields and researchers have used various methods to measure tissue resistivity and to identify the error sources in systems for measuring tissue resistivity at different frequencies (Tsai *et al.* 2002). As resistance measurements are generally easier and more reliable than capacitance measurements (Godin *et al.* 1991, Ackmann 1993, Ward *et al.* 1998), it is worth investigating whether the initial effort to clean the canal from conductive agents and then utilize second generation EALs can finally result in more stable measurements than those obtained with third generation EALs in conductive environments.

The aim of the present study was to compare *in vivo* the second generation EAL Apex Finder (Endo Analyzer 8001; Analytic Technology, Redmond, WA, USA) with the third generation EAL Root ZX analysing five different stages within the root canal instrumentation

procedure. The null hypothesis tested is that the two EALs produced different results under the same clinical situations.

Materials and methods

Teeth selection

Thirty-seven teeth, scheduled for extractions due to periodontal disease or orthodontic reasons, were selected. The teeth did not have metallic restorations nor roots with resorption, fractures, open apices, or radiographically invisible canals. Informed consent was obtained from each patient under a study protocol approved by an ethical committee from the University of Trieste. A standardized periapical radiograph was taken for each tooth in buccolingual projection to allow proper selection. The selected teeth included six second maxillary molars (three canals each), three first maxillary premolars (two canals each), four maxillary canines (one canal each), three maxillary central incisors (one canal each), two maxillary lateral incisors (one canal each), four first mandibular molars (three canals each), two second mandibular molars (three canals each), four first mandibular premolars (one canal each), five second mandibular premolars (one canal each), two mandibular canines (one canal each), two mandibular central incisors (one canal each) for a total of 64 canals. It must be noted that the original selected teeth were 40 (with 70 canals), but three teeth (six canals) were discarded due to damage that occurred during extraction.

Tooth preparation

All teeth were treated by the same operator under $\times 4.3$ magnification (Zeiss telescopes; Carl Zeiss Jena GmbH, Zeiss Group, Jena, Germany). After administration of local anaesthesia and isolation under rubber dam, the cusps were flattened with a tapered diamond bur (Number 845.314.012; Komet Brasseler, Lemgo, Germany) using a high-speed handpiece (Kavo Intramatic 25C; Kavo GmbH & Co., Biberach, Germany) under water irrigation to obtain fixed reference points. A conventional endodontic access was prepared using the same bur and a tapered stainless steel size 012 Batt bur (Dentsply Maillefer, Ballaigues, Switzerland) was used to smooth the pulp chamber walls. The number of canals and whether the pulp was vital (presence of bleeding) or necrotic upon entering the pulp chamber were recorded.

Each *in vivo* measure was always taken first with the Apex Finder and then with the Root ZX; measurements were considered as valid if the instrument remained stable for at least 5 s, otherwise the value was recorded as unstable measurement due to inability of the EALs to reveal a constant reading. Unstable measurements were not able to evaluate the accuracy of measurements provided by the EALS.

The EALs were used in five steps of the canal instrumentation:

1. The first measure was taken using a size 06 stainless steel K-file (F.K.G. Dentaire, La Chaux-de-Fonds, Switzerland) that was inserted into the root canal prior to any instrumentation or irrigation of the endodontic system. The Apex Finder was used with the panel wheel set at '5'. The clip was applied to the patient's lip, and the straight probe with the bifurcated tip was connected to the size 06 K-file in position inside the canal. The file was advanced into the canal until reading of the EAL showed a consistent 00. To confirm the measure the file was advanced less than 0.5 mm to verify that the dial flashed 00 and the audible signal could be heard, and then retracted to obtain the consistent 00 reading again. The silicone stopper on the inserted file was then set to the nearest flat anatomical tooth landmark and the distance between the stopper and the tip of the file was measured under $\times 4.3$ magnification to the accuracy of 0.25 mm. The Root ZX (J. Morita Corp.) was then used. The clip was applied to the patient's lip and the file holder was attached to the file. The file was advanced into the canal until the reading on the display flashed 'apex' and the audible continuous signal indicated that the anatomical foramen had been reached. The silicone stopper on the inserted file was then set to the flat anatomical tooth landmark, the file was retracted and the distance between the stopper and the file tip was measured under $\times 4.3$ magnification. The same procedure was repeated for each additional canal and for each other step of the clinical procedure.

2. The second measurement was taken after brief instrumentation with size 08-20 H-files (F.K.G. Dentaire) in the middle and coronal third of the canal and after irrigation with 70% isopropyl alcohol used as nonconductive irrigant (Pilot & Pitts 1997). The pulp chamber was gently dried with the air syringe prior to insertion of the size 06 K-file connected to EAL.

3. The third measurement was taken after lubricating the canal with RC-Prep (Hawe Neos Dental, Bioggio, Switzerland) using a size 06 instrument connected to the EALS.

4. The fourth measurement was taken after canal instrumentation: a modified double flared technique was performed using stainless steel K-files sizes 06 to 70 (F.K.G. Dentaire) and sizes 1, 2, 3, 4 Gates-Glidden burs (Dentsply Maillefer); lubrication was obtained with RC-Prep and irrigation with 5% NaOCl solution. Apical patency was maintained by using a size 06 K-file through the foramen during canal instrumentation. Measurement was obtained using a size 15 K-file connected to the EAL and inserted into canals previously irrigated with 5% NaOCl.

5. The fifth measurement was obtained using a size 15 K-file connected to the EAL after drying the instrumented canal with paper points.

Teeth were then extracted, immersed in 2.5% NaOCl for 10 min and all remaining organic residuals from external root surfaces were removed with a curette (Hu-Friedy Mfg. Co., Chicago, IL, USA). After a short rinse in tap water, a size 15 K-file was inserted until its tip was observed to reach the foramen under $\times 15$ magnification with a stereomicroscope (Zeiss Stemi 2000-C; Carl Zeiss): the corresponding length to the accuracy of 0.25 mm was recorded and compared with the values obtained with EALs. Collected data were: apex diameter at the end of instrumentation, apical or lateral ending of the canal terminus preparation and working length measured referring to the coronal side of the foramen.

Data obtained by both EALs were analysed statistically with general linear model (*P*-value set at 0.05; due to the different number of data within the groups the ANOVA test was not applicable); the Student's *t*-test was used to compare data obtained with the two EALs (*P*-value was set at 0.025).

The statistical analysis evaluated interactions of apical diameter, lateral or apical exit of the canal terminus, pulp vitality, distance from the apex, stage of the instrumentation and EAL on the error determined by difference between EAL measurement and the measurement obtained under the stereomicroscope.

Moreover within each step of instrumentation error was divided in four groups (0.00–0.25, 0.25–0.50, 0.50–0.75, 0.75–1.00 mm) and the error distribution was analysed using the chi-square test.

Results

Overall 24 necrotic and 40 vital pulps were recorded during the pulp chamber opening procedure. The root analysis under the stereomicroscope revealed a visible file tip in all specimens: in 42 specimens the foramen coincided with the root tip, whilst in 22 a lateral foramen was found.

Unstable measurements

Unstable measurements were found with both EALs tested and totalled 134 of the 640 measurements: unstable measurements were found 73 with the Root ZX compared to 61 with Apex Finder. No statistical difference was found between the two EALs for this parameter (Table 1).

The Apex Finder revealed more unstable measurements than Root ZX at the end of instrumentation with the canal flooded with NaOCl irrigant (step 4) with 58 unstable measurements versus only five with the Root ZX ($P < 0.05$). The Root ZX revealed more unstable measurements at stages 2, 3 and 5 (67 of 68) ($P < 0.05$). Statistical analysis revealed that apex diameter, pulp vitality, apical or lateral terminus of the root canal had no influence on unstable measurements.

Measurement accuracy

Accuracy was calculated only on stable measurements. Comparing the mean differences (regardless of the instrumentation stage) between measurements obtained with the two EALs and those obtained with the stereomicroscope, the ANOVA test overall demonstrated that the Root ZX had more precise measurements

Table 1 Number of unstable measurements obtained with the Apex Finder and Root ZX EALs at the five different clinical stages of the instrumentation

Step	Description	Apex Finder	Root ZX	<i>P</i>
1	Right after pulp chamber opening	2	0	0.8
2	After preliminary and partial cleaning of the pulp	0	25	<0.05
3	During instrumentation with EDTA wet canal	0	28	<0.05
4	At the end of instrumentation with NaOCl wet canal	58	5	<0.05
5	At the end of instrumentation with dry canal	1	14	<0.05

(-0.03 ± 0.39 mm) compared with the Apex Finder (-0.31 ± 0.46 mm) ($P < 0.05$).

The general linear model statistically analysed the influence of the endodontic parameters (apex diameter; position of canal terminus; stage of instrumentation; real distance to the apex of the file tip inside the canal when each measurement was recorded: this data was obtained by comparing the length of the shaft of the file in the canal with the length of the canal measured after tooth extraction) on EALs precision (calculated as difference between the EAL measurement and the measurement obtained under stereomicroscope) investigating both the influence of each single parameter or their combination thus revealing possible multiple parameter effects. Stage of canal preparation, apex locator and real distance to the apex of the file tip affected accuracy of the results ($P < 0.05$). Moreover, the precision of the EALs was influenced when testing multiple interaction: in particular, between stage of canal preparation and apex locator, between apex diameter and apex locator, between apex diameter and real distance to the apex ($P < 0.05$). The Student's *t*-test (in this case it was a bilateral test, and thus the significance was set at $P < 0.025$) allowed a comparison of the results obtained with the two EALs in relation to the apex diameter and stages of preparation. The analysis revealed that the precision of EALs was not affected by apex diameter alone (only with apex diameter size 20 Root ZX showed more precise measurements at all steps of instrumentation, $P < 0.025$), neither by the only presence of pulp inside the canal (only at stage 1 a statistical effect was found related to apex diameter size 30 where Root ZX revealed more precise measurements, $P < 0.025$). The

Student's *t*-test also revealed that the Apex Finder provided less precise measurements (higher mean differences with the stereomicroscope measurements) and higher SD compared with Root ZX at stages 1, 2, 3 and 4 (even if no statistical difference was found, $P > 0.025$), whilst after full instrumentation and drying (stage 5) the Apex Finder revealed more precise measurements ($P < 0.025$, Table 2).

Table 3 reports the number of data obtained with each EAL related to the error given by the comparison of the electronic versus the real measurement: it is remarkable that all measurements were confined between ± 1.5 mm from the apex and in particular that measurements were confined between ± 1 mm from the apex in 490 cases (out of 506). Chi-square test (significance at $P < 0.05$) demonstrated that the Root ZX revealed measurements mainly at 0.00–0.25 mm from the apex regardless of the stage of instrumentation, whilst the Apex Finder was 0.50–1.00 mm from

Table 2 Influence of the step of instrumentation on the mean values of the difference between EAL and stereomicroscope measurements

Step	Apex Finder ^a	Root ZX ^a	<i>P</i>
1	0.53 ± 0.49	0.04 ± 0.37	0.0397
2	0.42 ± 0.41	0.09 ± 0.42	0.9594
3	0.37 ± 0.42	0.09 ± 0.42	1.0000
4	-0.47 ± 0.23	0.02 ± 0.41	0.2030
5	-0.0 ± 0.21	-0.05 ± 0.32	0.0015

^aMean \pm SD.

Measurements at the stereomicroscope were obtained after teeth extraction with a size 15 K-file was inserted until its tip was observed to reach the foramen under $\times 15$ magnification: the corresponding length was recorded. Statistical difference ($P < 0.025$) was found only at step 5.

Table 3 Number of observations in relation to the measurement error obtained by comparing the electronic and real measurements for each of the two EALs

Stage of treatment	EAL	No. of measurements with error of mm				Total of valid measurements	Unstable measurements	Chi-square test
		0.00–0.25	0.25–0.50	0.50–1.00	1.00–1.50			
1	Root ZX	47	6	11	0	64	0	0.0000
1	Apex Finder	11	7	36	8	62	2	0.0000
2	Root ZX	25	5	7	1	38	26	0.0000
2	Apex Finder	18	13	29	4	64	0	0.0001
3	Root ZX	24	4	8	0	36	28	0.0000
3	Apex Finder	23	13	25	3	64	0	0.0002
4	Root ZX	41	11	7	0	59	5	0.0000
4	Apex Finder	6	0	0	0	6	58	0.0004
5	Root ZX	39	7	4	0	50	14	0.0000
5	Apex Finder	61	1	1	0	63	1	0.0000
Total		295	67	128	16	506	134	

the apex at stages 1, 2 and 3 and at 0.00–0.25 at stages 4 and 5.

Discussion

The present study evaluated two EALs that were developed with different technologies and that measure differently the electric phenomena inside the root canal. The electrical characteristics of biological tissues may be described by an equivalent circuit. All EALs utilize human tissues as a component to close an electrical circuit. One electrode of the locator is connected to the endodontic file, whereas the other is connected to a clip that touches the oral mucosa; as the file is introduced into the root canal, the circuit is completed. As the file is moved further apically, the electrical characteristics change, and the maximum change is found when the file tip is at the foramen.

A large part of the literature comprises clinical investigations of the accuracy of commercially available instruments (Inoue & Skinner 1985, Fouad *et al.* 1990, McDonald & Hovland 1990, Arora & Gulabivala 1995) but there appears to be a relatively little work examining the electrical characteristics of the root canal environment.

Modern EALs use alternating current and detect changes in the impedance of the canal; impedance is the ratio between applied voltage and resulting current in an alternating current electrical circuit. The total opposition to the alternating current flow in an electric circuit is expressed in ohms and is made of two components, resistive and reactive: the reactive components depends on magnetic (inductance) and capacitive (capacitance) effects. In circuits with a reactive component the magnitude of opposition is frequency-dependent, whilst the resistive component exerts a static opposition to flow. The inductive effects occurring in biological tissues when using EALs are negligible; only resistance and capacitance should therefore be introduced in equivalent electrical circuits (Kobayashi *et al.* 1991a, Kobayashi & Suda 1994, Meredith & Gulabivala 1997, Pilot & Pitts 1997).

The accuracy of the second generation EALs has been found to be between 83.0 and 93.4% (Plant & Newmann 1976, Inoue & Skinner 1985, Trope *et al.* 1985, Kaufman *et al.* 1989, McDonald & Hovland 1990). The major remaining disadvantage with the second generation EALs is that the presence of highly conductive conditions (i.e. blood or conductive irrigants in the canal, large apical diameter, and periapical lesions) can lead to measurement errors (Sunada 1962,

Ushijama 1983, Ushijama *et al.* 1988, Kobayashi 1995).

The third generation of dual frequency apex locators was developed to reduce these problems. They are frequency-dependent apex locators also supplied by alternating current, but operating on the principle that they measure different values of impedance between electrodes depending on the signal frequencies used. In fact, the root canal acts as a complex electrical network, in which the rate of resistance changes with the distance from the apex and it is different for different frequencies (Meredith & Gulabivala 1997).

It has been reported (Kobayashi & Suda 1994) that the capacitance of the endodontic space is increased using a conductive solution inside the canal and this phenomenon has been declared to affect the result of electronic measurements; when a file tip is located away from the apical foramen, the root canal should have only a negligible capacitance, but when the file reaches the immediate proximity of the apical foramen, the magnitude of the capacitance of the canal should suddenly increase. The larger capacitance at the apical constriction has been properly manipulated, and has allowed the development of Root ZX (Kobayashi & Suda 1994), which works at frequencies of 8 kHz and 400 Hz. With an electrolyte solution inside the canal, two canal's impedances (Z_1 and Z_2) are simultaneously measured for the two frequencies f_1 and f_2 . When the electrolyte is replaced by another one, if impedance Z_1 changes at the same rate as Z_2 , the ratio of Z_1 to Z_2 would not be modified; thus this ratio yields a definite value which would represent the position of the electrode inside the canal irrespective of the canal contents (Kobayashi & Suda 1994).

On the contrary, Meredith & Gulabivala (1997) reported that there is no trend to suggest a relationship between the capacitive components measured and root canal length, and that the series resistances are the main component to measure the complex impedance of a root canal. Either in dry or containing deionized water, canals the same authors (Meredith & Gulabivala 1997) measured a clear rise in series resistance (RS) with increasing distance from the radiographic apex and found an overall decrease in both the series and the parallel *capacitive* components, suggesting a complex relationship between the impedance of the smear layer and bulk dentine (Meredith & Gulabivala 1997).

These phenomena surely influence the overall accuracy of all EALs, irrespective of their technical characteristics. Inaccuracy with commercial instruments has been found especially when they have been

used in wet root canals (Abbott 1987, Huang 1987, Meredith & Gulabivala 1997). Other negative factors influencing the accuracy of EALs have been reported, e.g. presence of electroconductive substances in root canals (Abbott 1987, Huang 1987), periapical disorders (Abbott 1987), diameter of apical foramen (Stein *et al.* 1990, Fouad *et al.* 1993) and shape and volume of the measurement file (Vachy *et al.* 1985). Operator ability has also been reported to influence measurements, particularly with the Apex Finder compared with third generation EALs (DeMoor *et al.* 1999).

The results of the present study confirm that EALs can accurately determine the canal length within 0.5 mm from the apical constriction (Fouad *et al.* 1990, 1993, Vajrabhaya & Tepmongkol 1997) regardless of pulp vitality and presence of lateral apical foramina. These findings are in accordance with previous reports (Mayeda *et al.* 1993, Vajrabhaya & Tepmongkol 1997, Pagavino *et al.* 1998), but not with others that revealed a higher accuracy of EALs in vital canals (94.4%) rather than in necrotic canals (81.8%) (Arora & Gulabivala 1995) or showed that the Root ZX is more precise in teeth with an apical foramen coincident with the tip of the root compared to teeth with lateral foramina (Pagavino *et al.* 1998).

Results of the present study showed that measurement accuracy is related to the contents of the canal, type of EAL used and real distance from the apex (Table 3). Considering the total number of measurements obtained, the Root ZX revealed more precise measurements as confirmed by a lower mean distance value from real length measured by the stereomicroscope (0.03 ± 0.39) compared with the Apex Finder (0.31 ± 0.46 ; $P < 0.05$). Considering each single phase of the instrumentation, the Apex Finder revealed less precise measurements compared with the Root ZX at stages 1, 2, 3 and 4 (no statistical difference), whilst the Apex Finder was most accurate under the dry test conditions (step 5; $P < 0.05$, Table 2), even if the clinical relevance of this slight higher accuracy may be questionable. This is in agreement with previous studies (Pilot & Pitts 1997) that reported for the Apex Finder a higher prediction error for more conducting solutions and a more precise determination of file placement with nonconducting irrigants such as RC-Prep or isopropyl alcohol.

Stages 2, 3 and 5 of the present study were considered as low canal conductivity conditions whilst stage 4 was considered as high canal conductivity condition; stage 1 depended on the natural canal content, i.e. vital or dystrophic or necrotic pulp, and it was not classified in relation to conductivity.

Conductivity testing of some irrigants allowing the ranking of the most commonly used endodontic solutions from most to least conductive: 5.25% NaOCl solution, 14.45% EDTA sodium, normal saline and finally RC-Prep similar to 70% isopropyl alcohol, with the last two being essentially nonconductive (Pilot & Pitts 1997). The changes in electrical characteristics when the foramen is approached and passed are minimal when conductive solutions are inside the canal (Pilot & Pitts 1997); this condition would complicate electrical determination of the foramen (Pilot & Pitts 1997). In fact, the mean resistance for dry canals has been reported to be markedly higher than for those containing fluid, ranging from 22.19 k Ω (apex) to 92.07 k Ω (5 mm to the apex), in comparison with 7.46 k Ω (apex) to 8.92 k Ω (5 mm to the apex) for canals containing NaOCl (Meredith & Gulabivala 1997).

Besides its lubricating and chelating ability, RC-Prep viscosity has been reported to produce an insulating effect between the canal wall, tissue debris, and file, and this may reduce some of the variables that affect electronic root length determination allowing higher impedance changes as the foramen is approached (Pilot & Pitts 1997).

According to these observations the results of the present study confirmed that the presence of nonconductive solutions inside the endodontic space achieves favourable effects on Apex Finder but negative effects on Root ZX. In fact, the use of alcohol rinses (i.e. step 2) and RC-Prep (i.e. step 3) allowed the Apex Finder to obtain very precise measurements with stable values (Table 3), whilst created difficulties as indicated by the high number of unstable measurements for the Root ZX, thus revealing clinical problems with this EAL in cases using low conductive situations.

In particular sudden measurement changes can occur due to slight movements of the file tip in the canal. This might be due to the capacitance variations that occur due to the geometric variations of the equivalent electrical circuit that occurs within the tissues during measuring. The capacitance in fact is a parameter related to both the electrical properties of the materials involved in the system and the system geometry itself.

The main differences in accuracy of the two EALs are represented in Table 3, also considering the number of unstable measurements: the Apex Finder resulted in more precise measurements in instrumented and dry canals (step 5, $P < 0.05$) and showed acceptable working capabilities (considering the number of

unstable measurements) also with apex bleeding at step 1, whilst the presence of NaOCl solution in the canal almost inhibited its working capability (58 unstable measurements out of 64, Table 3). Conversely, the Root ZX revealed a more variable behaviour depending on the clinical situation: unstable measurements were obtained in cases of high level of NaOCl in wide canals (five of 64, Table 3), or in narrow canals at stages 2 and 3, thus in cases of low conductive situations (26 and 28 unstable measurements out of 64, Table 3). On the contrary, the *in vivo* results revealed precise functioning at stages 1 and 4 when conductive materials was contained in the canal (organic residual pulp tissue or NaOCl irrigant solution).

In accordance with previous reports (Huang 1987, Meredith & Gulabivala 1997, Pilot & Pitts 1997), excellent clinical results were obtained at step 5 (end of the instrumentation) with both EALs confirming their clinical reliability in dry, enlarged and clean canals.

Results of the present study revealed higher precision of both EALs when approaching the canal terminus (Table 3), probably due to the fact that the higher impedance changes occur when the distance to the apex is -0.25 mm and $+0.5$, whilst impedance remains virtually constant at lengths shorter than -0.5 mm of the tooth length (Pilot & Pitts 1997).

Huang (1987) underlined the importance of apex diameter by considering that EALs measured only physical phenomena by the file passing through the apical constriction: an electric gradient would be recorded if no electrolytes are present inside the root canal or if the apical diameter is not too wide. If both factors are present the measurement could be imprecise (Huang 1987). The present data are not completely in agreement with these results as the present study revealed minor influence of the apex diameter on EALs measurements. This is in agreement with the hypothesis that third generation EALs, such as Root ZX, have been designed to reveal very small impedance changes similar to the ones that can be found in proximity of the apex in canals containing electrolytic solutions. On the contrary, the Root ZX appeared to be affected by very fine movements of the file and the apex location resulted sometimes cumbersome to the operator.

Conclusions

1. The results of the present study revealed that both of the tested EALs were able to measure the canal length with a high level of precision. Statistically significant difference between the two EALs in terms

of measurement precision was found only at the end of the instrumentation and after complete drying: at that step the Apex Finder had a higher precision rate. Nevertheless, this difference may not be clinically relevant due to the very small difference in term of measurement values.

2. Within the different variables tested in the present study, pulp vitality and position of the foramen in relation to the root did not influence the functioning of the EALs.

3. The number of unstable measurements reported in the present study revealed a different clinical behaviour of the two EALs. The Apex Finder revealed several unstable measurements in the presence of NaOCl irrigant, whilst the Root ZX had unstable measurements in low conductive situations.

4. The present study suggests that second generation EALs are able to function better in low conductive situations, whilst third generation EALs have a better clinical behaviour in the presence of highly conductive solution in the canal. Thus, the data confirmed the clinical impression that the Root ZX works better in wider canals with NaOCl, showing high precision; nevertheless this high precision was related to some clinical difficulties in obtaining stable values, as small movements of the file determine changes in the instrument data. The Apex Finder was unable to reveal very small impedance changes thus it was more 'user friendly' in dry conditions and very stable in narrow canals; however it was unable to give a stable measurement in the presence of conductive irrigants.

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